Far-field Model for Desalination Brine Discharges to the Ocean Through a Multiport Diffuser

Anton Purnama*1

Department of Mathematics and Statistics
College of Science, PO Box 36, Sultan Qaboos University, Al-Khod PC 123, Muscat, Oman

*1antonp@squ.edu.om

Abstract

A far-field mathematical model for desalination brine discharge through a long sea outfall with multiport diffusers is developed using a two-dimensional advection-diffusion equation based on a flat seabed that incorporates the effect of a tidally oscillating flow. Using the asymptotic approximation of the analytical solutions, the maximum diffuser-induced shoreline's brine concentration is formulated to predict the long-term potential impact of brine discharge from a seawater desalination plant in the coastal waters. The result shows that a long sea outfall with a perpendicular line diffuser (to the flow direction) is capable of thoroughly mixing and diluting the discharge brine plume into the far-field.

Keywords

Desalination Brine Discharges; Mathematical Model; Multiport Diffuser; Sea Outfall; Long-Term Impact Assessment

Introduction

As desalinated water is indispensably required at all costs in hot and arid climate countries, there are intense seawater desalination activities along certain coastlines of the Arabian Gulf, Red Sea, Mediterranean Sea, and the Gulf of Oman. In particular, more than half of the world's desalination plants are constructed along the coasts of the Arabian Gulf, Gulf of Oman and Red Sea [Lattemann and Hopner, 2008]. Thus, along such coastal areas, many seawater desalination plants are commonly found to be operated closely together. Furthermore, as the needs for desalinated water are steadily increasing, not only are the number of new large scale desalination plants growing, the existing plants are also gradually increasing their water production capacities. Like any large scale industrial process, seawater desalination unfortunately also has its potential environmental impacts and is a serious threat to marine ecosystems [Sheppard et al., 2010]. Desalination plants extract large volumes of seawater and discharge hypersaline brine, a reject concentrate stream, back into the marine environment [Roberts et al., 2010]. The unwanted brine product is primarily seawater but at a more concentrated level, with a concentration factor of as high as two times the typical seawater salinity [Voutchkov, 2011].

Most large scale coastal seawater desalination plants dispose of their concentrate via long outfall pipes that stretch far into the ocean, and as concentrate brine stream enters the receiving marine waters, it creates a high salinity plume [Purnama et al., 2011; Bleninger and Jirka, 2008]. Once the conventional single ocean outfall is no longer sufficient to obtain the desired degree of brine plume dilution, the engineering solution utilizing the best available technology is required, where a multiport diffuser would be installed at the pipe-end to rapidly dilute the concentrate. Without proper dilution, the brine plume will tend to sink and propagate down the slope for hundreds of meters, harming the ecosystem along the way, and most at risk are the benthic marine organisms living at the sea bottom [Bleninger and Jirka, 2008; Voutchkov, 2011]. The worst situation may occur along the highly populated coastal areas of the Arabian Gulf, Gulf of Oman and Red Sea, where multiple sea outfalls discharge large volumes of desalination brine [Lattemann and Hopner, 2008; Sheppard et al., 2010].

A multiport diffuser is a linear structure consisting of many closely spaced ports or nozzles designed to discharge a series of concentrate streams. Figure 1 shows two submerged marine outfall systems used for discharging brine from the Barka (co-location) power generation and seawater desalination plants in the Gulf of Oman [Purnama et al., 2011]. Each outfall system is designed for a maximum capacity of 122,100

m^3/h to discharge the cooling water from the power generation plants and mix it with brine (and other effluents) from seawater desalination plants. The multiport diffusers are designed in two nested V shapes, and each pair of diffusers diverges at an angle of 30 degrees on either side of the outfall pipeline. The second (shorter) outfall pipe length is about 650 m, while the first (longer) outfall pipe length is about 1200 m, and the distance between the two discharge points is 1000 m.

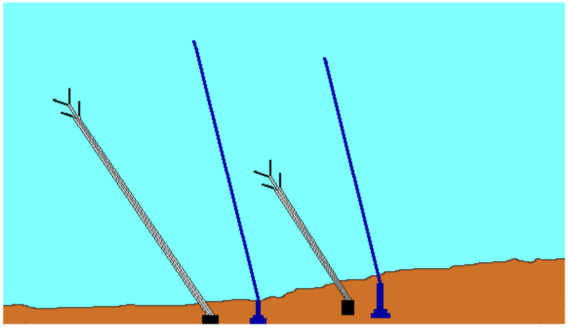

FIG. 1 SEAWATER INTAKE AND MARINE OUTFALL SYSTEMS OF BARKA PLANTS, OMAN

To demonstrate the effectiveness of a multiport diffuser in diluting the brine streams, sophisticated laboratory experiments have been conducted to visually replicate and capture the process of overlapping discharge plumes from such a diffuser [Roberts and Tian, 2004]. However, owing to the complexity of mixing processes and highly variable nature of the sea, the field numerical solutions are still far from perfect and difficult to verify. For positively buoyant discharges, the laboratory experiments show that immediately after release from the multiport diffusers, vigorous and rapid dilution of plumes occurs [Bleninger and Jirka, 2008; Jirka, 2006]. At the end of this near-field region, adjacent plumes collapse and interact with each other and merge to form a rising curtain, which then continues to drift away with the flow. Such a multiport diffuser improves the mixing of brine plumes substantially with additional dilutions of between about 5 and 20 above the single outfall dilution [Jirka, 2006; Bleninger and Jirka, 2008; Palomar and Losada, 2011]. In an attempt to answer the question, "Does the multiport diffusers improving dilution persist into the far-field?", a mathematical model using a two-dimensional advection-diffusion equation based on a flat seabed is developed, which incorporates the effect of a longshore tidal current oscillating with a period of half a lunar day.

While the far-field modelling in this paper involves drastic simplifications, key physical mixing and dispersion processes are represented, and thus the mathematical model remains useful in providing a qualitative understanding and in suggesting general behaviour of the marine outfall brine discharge plume from a desalination plant [Purnama, 2012; Roberts et al., 2010; Palomar and Losada, 2011]. Due to the unpredictable sea conditions, very little information is available on the model parameters, and for model illustrations, outfall plume simulations are carried out for some values of the parameters [Al-Barwani and Purnama, 2008; Kay, 1990; Purnama and Al-Barwani, 2006]. The long-term environmental impact assessments of marine outfall brine discharge have become increasingly important, both as a result of public concern and scientific awareness and because of the increasing scale of seawater desalination activity. As it has also become a key issue to obtain permits to build a new marine outfall, often considerably influencing desalination plant commissioning and design, regulatory requirements and strategies should be properly defined based on the protection of a sustainable marine environment [Bleninger and Jirka, 2008; Voutchkov, 2011].

Model Formulation

As we are only concerned with the effect of oscillating currents on the long-term (far-field) desalination brine plume, a highly simplified semi-infinite flat seabed is considered, where the shoreline is straight and of a constant water depth [Al-Barwani and Purnama, 2008; Kay, 1990; Purnama and Al-Barwani, 2006; Purnama and Kay, 1999; Shao et al., 2008]. The longshore current is assumed to be uniform over water depth and remains in the x-direction parallel to the shoreline. A simple model of a longshore current that consists of a steady (residual) drift v and a periodic component with amplitude U can be represented by $u(t) = v + U \sin \omega t$ [Kay, 1990; Macdonald and Weisman, 1977; Purnama and Kay, 1999; Shao et al., 2008]. Although the brine plume is observed to be oscillating back and forth, the net transport depends on the ratio of the drift current to tidal amplitude.

In practice, a modern coastal seawater desalination plant marine outfall's brine discharge is made via diffusers and utilizes the best available technology to promote rapid initial dilution [Jirka, 2006], and it is also assumed that, in the far-field, the outfall's brine plume is vertically well mixed over the water depth. The dispersion processes are represented by the

longitudinal diffusivity D_x and lateral diffusivity D_y. Note that for shallow coastal waters, the dispersion in the vertical direction occurs much faster than that in the lateral direction [Smith and Scott, 1997]. For simplicity, other complexities such as density and temperature are ignored.

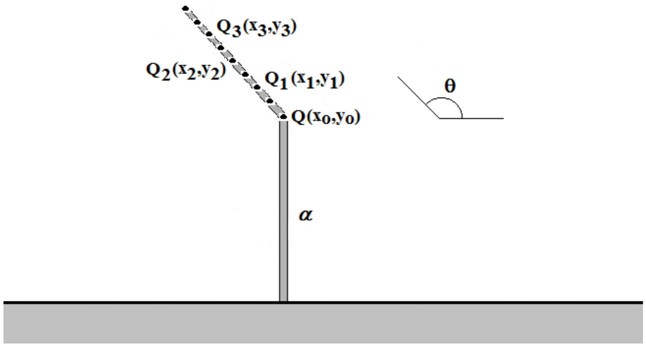

FIG. 2 DIAGRAM OF AN OCEAN OUTFALL WITH A MULTIPLE DIFFUSER

For a single outfall, as illustrated in Figure 2, the desalination brine stream is considered to be steadily discharged, starting from the initial time t_i, at a rate Q_0 from the position $(x_0 = 0, y_0 = \alpha)$. Extension for a multiport line diffuser (installed with an angle θ at the end single outfall pipe) with n ports equally spaced apart with distance d along the extended outfall pipe, the position of each port is represented by $(x_k = -k\ell, y_k = \alpha + kh)$, where $h = d\sin\theta$ is the port's (offshore) and $\ell = d\cos\theta$ (along the shore) separation distances. The single outfall is the first port in a multiport diffuser, and since the total brine load is distributed equally, each port discharges at a rate $Q_k = Q_0/n+1$ [Bleninger and Jirka, 2008]. It should also be noticed that both values of h and ℓ are small compared to α, and for the case of Barka plant's multiport diffusers, $h = 6.5$ m, $\ell = 3.75$ m and $\alpha = 576.5$ m [Purnama et al., 2011].

For a multiport diffuser, by applying a linear superposition, the two-dimensional advection-diffusion equation for the far-field plume concentration c is given by

$$\frac{\partial c}{\partial t} + u(t)\frac{\partial c}{\partial x} - D_x\frac{\partial^2 c}{\partial x^2} - D_y\frac{\partial^2 c}{\partial y^2} = \delta(t - t_i)\sum_{k=0}^{n} Q_k\,\delta(x - x_k)\left[\delta(y - y_k) + \delta(y + y_k)\right]$$

where δ, the Dirac delta function, represents a point source term, and in order to satisfy the boundary condition at $y = 0$, an imaginary source term is added at $(x_k, -y_k)$. In terms of the dimensionless variables, the solution is given by

$$C_* = \int_0^{T_i}\frac{dT_0}{T_0}\sum_{k=0}^{n} q_{k*}\exp\left[-\frac{\lambda}{T_0}\left\{X + kL - X_0(T)\right\}^2\right]\left\{\exp\left[-\frac{\lambda\eta\{Y - \Lambda - kH\}^2}{T_0}\right] + \exp\left[-\frac{\lambda\eta\{Y + \Lambda + kH\}^2}{T_0}\right]\right\}$$

where $C = 4\pi c\sqrt{D_x D_y}/Q_0$, $q_{k*} = Q_k/Q_0$, $V = \nu/U$, $\lambda = U^2/4\omega D_x$, $\eta = D_x/D_y$, dimensionless position $X_0(T) = VT_0 - \cos T + \cos(T - T_0)$, dimensionless time $T_i = \omega t_i$, $T_0 = T - \omega t_0$, and dimensionless length $X = \omega x/U$, $Y = \omega y/U$, $\Lambda = \omega\alpha/U$, $L = \omega\ell/U$ and $H = \omega h/U$.

The interaction and merging process of multiport plume behaviour is controlled by the interplay of the model parameters [Al-Barwani and Purnama, 2008; Kay, 1990]: V, the ratio of the drift current to tidal amplitude; λ, the distances by which the plume is transported and spread over by advection to that by longitudinal diffusion [Macdonald and Weisman, 1977]; and η, the ratio of longitudinal to lateral diffusivities [Smith and Scott, 1997]. The flow periodicity enables us to restrict our observation time T in a single representative tidal cycle. Other parameters are related to the multiple diffusers, such as Λ the single outfall (offshore) distance, H the port's (offshore) and L the (along the shore) separation distances. Note that both values of H and L are much smaller than Λ, and for a multiport line diffuser with n ports, $q_{k*} = 1/n+1$.

As the sensitive areas for the evaluation and assessment of the long-term potential impact of marine outfall discharge would be at the beach, we therefore use, as an appropriate measure, the concentration values along the shoreline [Al-Barwani and Purnama, 2008; Purnama and Al-Barwani, 2006]. On substituting $y = 0$, we obtain

$$C_* = \frac{2}{n+1}\int_0^{T_i}\frac{dT_0}{T_0}\sum_{k=0}^{n}\exp\left[-\frac{\lambda}{T_0}\left(\left\{X + kL - X_0(T)\right\}^2 + \eta\left\{\Lambda + kH\right\}^2\right)\right].$$

If we are only interested in the long-term impact, i.e. in the limit as $T_i \to \infty$, then the term $\cos(T - T_0)$ may be neglected as it has little contribution to the integral [Purnama and Kay, 1999]. From the integral formula $\int_0^{\infty}\frac{dx}{x}\exp\left(-\frac{A}{x} - Bx\right) = 2K_0\left(2\sqrt{AB}\right)$, where K_0 is a modified Bessel function of the second kind [Gradshteyn and Ryzhik, 1980], the long-term concentration at the beach can be simplified to

$$C_{*\infty} = \frac{4}{n+1}\sum_{k=0}^{n}\exp\left(2\lambda V\{X+kL+\cos T\}\right)K_0\left(2\lambda V\sqrt{\{X+kL+\cos T\}^2+\eta\{\Lambda+kH\}^2}\right).$$

Next, using the asymptotic representation $K_0(x)\approx\sqrt{\pi/2x}\exp(-x)$, we can approximate further

$$C_{*\infty}\approx\frac{1}{n+1}\sum_{k=0}^{n}\sqrt{\frac{4\pi}{\lambda V(X+kL+\cos T)}}\exp\left(-\frac{\lambda V\eta\{\Lambda+kH\}^2}{X+kL+\cos T}\right).$$

For a single outfall, the maximum long-term concentration at the beach remains constant throughout the tidal cycle [Al-Barwani and Purnama, 2008], which implies that there is no time at which the maximum possible concentration level at the beach is worse than that at any other time. Thus, by replacing X with $X_{\max}=2\lambda V\eta\Lambda^2-\cos T$, the value where the maximum of the single outfall shoreline concentration occurs, the maximum long-term shoreline's concentration for the multiport discharge is finally approximated by

$$C_{*\max}\approx\frac{1}{(n+1)\lambda V}\sqrt{\frac{4\pi}{\eta}}\sum_{k=0}^{n}\frac{1}{\sqrt{2\Lambda^2+kL/\lambda V\eta}}\exp\left(-\frac{\{\Lambda+kH\}^2}{2\Lambda^2+kL/\lambda V\eta}\right).$$

It is easy to obtain, for the single outfall where $n=0$, $H=0$ and $L=0$, the maximum shoreline's concentration $C_{*0}=\frac{1}{\lambda V\Lambda}\sqrt{\frac{2\pi}{\eta e}}$.

Single Short Outfall Discharge

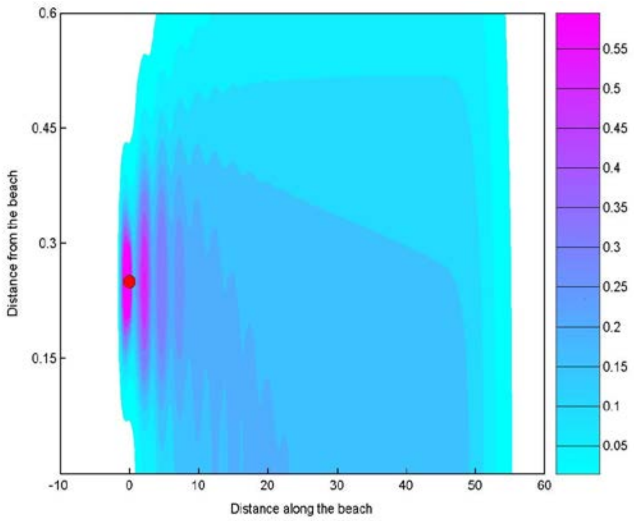

FIG. 3 SIMULATED BRINE PLUMES FROM A SINGLE SHORT OUTFALL DISCHARGE

The effect of the oscillating flows on the mixing and dissolving of single outfall brine discharges into the sea are illustrated graphically by plotting the results of numerical integrations of the solution by setting $n=0$, using the parameter values $V=0.4$, $\lambda=15$ and $\eta=25$.

Figure 3 shows a characteristic desalination brine plume drifting along and spreading towards the beach following a steady discharge for $T_i=42\pi$ from a short outfall located at $\Lambda=0.25$. The peakiness of the plumes reflects the physical feature of the flow oscillations. Note that the actual plumes are elongated in the *x*-direction, and the larger drift currents efficiently spread the plume over large distances downstream of the outfall. Due to flow oscillations, a concentration peak is also formed on the upstream side of the outfall [Al-Barwani and Purnama, 2008; Purnama and Al-Barwani, 2006].

Similarly, the concentration at the beach is plotted in Figure 4 following steady discharges for $T_i=30\pi$ and $T_i=60\pi$. The effect of oscillatory flow is clearly shown up to the time when the maximum concentration is reached. For comparison, the approximated long-term concentration at the beach is also plotted in Figure 4. From a regulatory viewpoint, since it remains constant throughout the tidal cycle [Al-Barwani and Purnama, 2008], the value of maximum concentration C_{*0} can be used as the numerical upper limit for a regulatory measure in the long-time impact of sea outfall discharge. Furthermore, due to the very long tail feature of the long-term concentration at the beach, the value of $X_{\max}$ could also be used as a minimum standard distance to permit the construction of a new outfall from the existing long sea outfall.

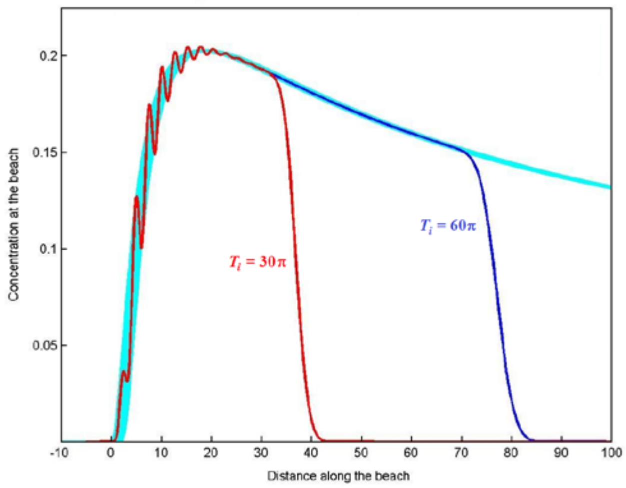

FIG. 4 LONG-TERM CONCENTRATION AT THE BEACH FOR A SINGLE SHORT OUTFALL DISCHARGE

The maximum concentration at the beach as given by $C_{*0}=\frac{1}{\lambda V\Lambda}\sqrt{\frac{2\pi}{\eta e}}$ is inversely proportional to the single outfall distance Λ. This result agrees with the

standard practice of building a longer sea outfall in order to minimize its potential environmental impact [Institution of Civil Engineers, 2001; Kay, 1990; Purnama and Kay, 1999]. In terms of the brine plume dilution, which is defined as the ratio of the initial concentration at the outfall discharge point to that at a given location, the minimum dilution for a single short outfall discharge is illustrated in Figure 5. A minimum dilution value of 4.93 is obtained for $\Lambda = 0.25$ which increases by 20% to 5.92 when the outfall length is extended to $\Lambda = 0.3$, and increases by 40% to 6.91 when the length is extended to $\Lambda = 0.35$.

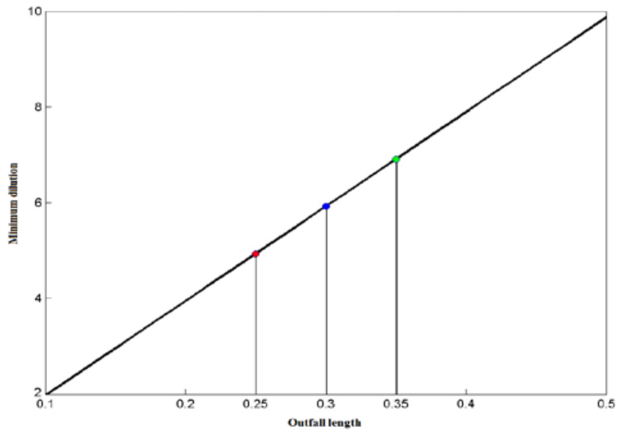

FIG. 5 MINIMUM DILUTION FOR A SINGLE SHORT OUTFALL DISCHARGE

Multiport Diffuser Discharge

For a large volume desalination brine discharge, the engineering practice is to distribute the brine stream over a large expanse by installing a multiport diffuser at the end of a long outfall [Bleninger and Jirka, 2008; Jirka, 2006]. For the quantitative illustration, a (perpendicular) line diffuser design is considered, where the line diffuser, consisting of a series of n ports equally spaced by the offshore separation distance H, is placed in the (offshore) y-direction perpendicular to the current direction. This particular multiport design has the longest (offshore) extension to the single outfall length, and will therefore give the smallest value of maximum concentration at the beach.

Setting $L = 0$ and $H = D$, since the installed angle $\theta = \pi/2$, we can simplify the maximum long-term shoreline's concentration further

$$C_{*\max} \approx \frac{C_{*0}}{n+1}\sum_{k=0}^{n}\exp\left(-\frac{kH}{2\Lambda}\left\{2+\frac{kH}{\Lambda}\right\}\right).$$

Thus, using the fact that H/Λ is small, we can approximate the exponential terms and obtain

$$C_{*\max} \approx \frac{C_{*0}}{n+1}\sum_{k=0}^{n}\left[1-k\left(\frac{H}{\Lambda}\right)-\frac{k^2}{2}\left(\frac{H}{\Lambda}\right)^2\right],$$

and finally, after summing for n ports,

$$C_{*\max} \approx C_{*0}\left[1-\frac{n}{2}\left(\frac{H}{\Lambda}\right)-\frac{n(2n+1)}{12}\left(\frac{H}{\Lambda}\right)^2\right],$$

where $(n-1)H/\Lambda$ is the (total) length of the line diffuser (relative to the single outfall length). As the number of ports increases, and the offshore distance is longer, the multiport diffuser maximum shoreline's concentration becomes smaller than that of the single outfall maximum value.

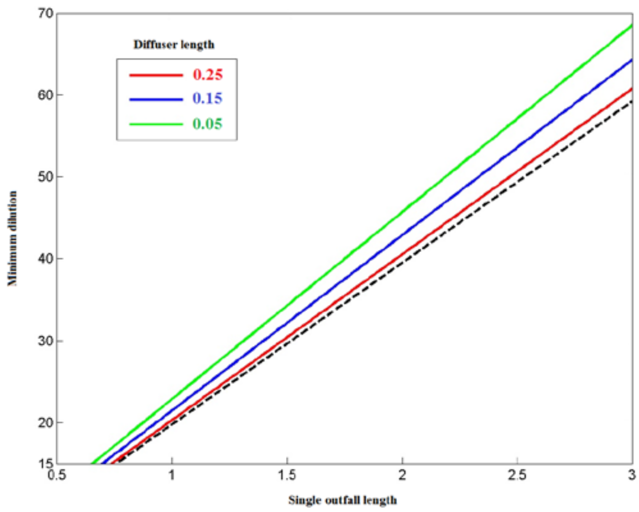

FIG. 6 MINIMUM DILUTION FOR A LONG OUTFALL WITH A MULTIPORT DIFFUSER DISCHARGE

Figure 6 shows the minimum dilution for a multiport diffuser installed at the end of a long single outfall with the port's separation distance $H/\Lambda = 0.01$ for three values of the line diffuser length $(n-1)H/\Lambda = 0.05$, 0.15 and 0.25, which is in agreement with the general fact that a multiport diffuser improves the mixing of desalination brine plumes substantially, mainly because the individual plumes are collapsed and swept away rapidly by the longshore current. The long-term minimum dilution for a single outfall discharge (without multiport diffusers) is shown by the dashed line. In particular for a long single outfall length $\Lambda = 2.0$, an additional increase of 1.03 (above the single outfall minimum dilution of 39.46) is obtained for a 6-port line diffuser, an additional increase of 3.38 can be achieved by increasing the number of ports to 16, and an additional increase of 6.19 is obtained for a 26-port line diffuser.

To exclude the long-term effect of the single long outfall, the brine plume additional increase in

minimum dilution (above that of the single outfall value) for a multiport diffuser is defined as $1/C_{*\max} - 1/C_{*0}$. Figure 7 shows the additional increase in minimum dilution for a multiport diffuser installed at the end of a long single outfall $\Lambda = 1.5$ for three values of the port's separation distance $H/\Lambda = 0.01$, 0.015 and 0.02. In particular for a 15-port line diffuser, an additional increase of 2.53 (above the single long outfall minimum dilution of 29.60) is obtained for $H/\Lambda = 0.01$; which increases to 4.08 as H/Λ increases to 0.015, and an additional increase of 5.87 is achieved for $H/\Lambda = 0.02$.

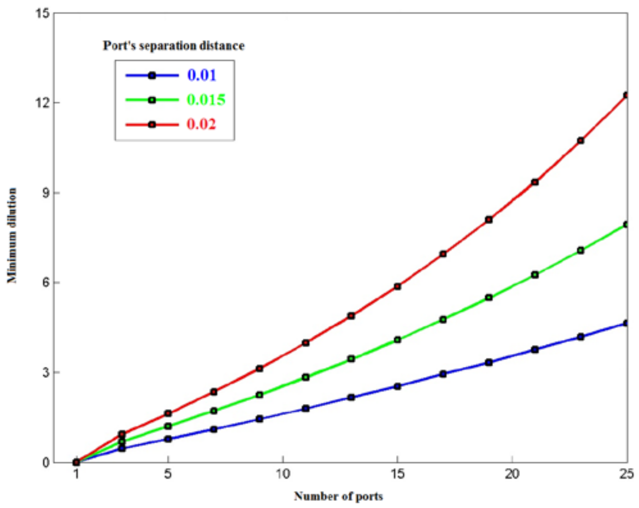

FIG. 7 MINIMUM DILUTION FOR A MULTIPORT DIFFUSER DISCHARGE

Conclusions

Long sea outfall discharge is a practical way to dispose of municipal or industrial effluent wastes as it gives the maximum possible separation of the discharge from people [Institution of Civil Engineers, 2001]. Such steady discharges are commonly found to be operated clustered together from plants or factories situated in highly populated coastal areas, e.g. treated effluents from sewage treatment plants [Signell et al., 2000], toxic contaminants from industrial installations [Institution of Civil Engineers, 2001], cooling water from power generation plants [Macqueen, 1978; Macqueen and Preston, 1983], and concentrate brine wastewater from seawater desalination plants [Bleninger and Jirka, 2008; Lattemann and Hopner, 2008; Purnama and Al-Barwani, 2006; Roberts et al., 2010; Palomar and Losada, 2011; Voutchkov, 2011]. The coastal areas are developing areas of industry and population, and sandy beaches are popular holiday resorts occupied by tourists for recreation and swimming. Therefore, reliable predictions of the long-term mixing and dispersal of the discharge plume are crucial for effective sea outfall design and operation that ensures a minimal impact on the coastal and marine environments and controls the public health risks from hazards that may be encountered in recreational use of coastal and marine environments [Voutchkov, 2011].

As the long-term detrimental impacts of a coastal desalination plant marine outfall's steady discharge to the receiving coastal waters are believed to be minimal, the number of seawater desalination plants worldwide is rapidly increasing. For a large volume desalination brine discharge, the engineering practice for modern marine outfall systems is to install a multiport diffuser at the end of a long outfall pipe [Bleninger and Jirka, 2008; Jirka, 2006; Palomar and Losada, 2011]. The far-field process of overlapping buoyant brine discharge plumes from such a diffuser can be modeled using a mathematical model [Purnama, 2012; Palomar and Losada, 2011]. In this paper, the long-term maximum diffuser-induced shoreline concentration is formulated, and the results for the perpendicular line diffuser (to the current direction) are in agreement with the fact that a multiport diffuser with 25 ports is capable of thoroughly mixing and diluting the brine discharge plume into the far-field with an additional increase in minimum dilutions of more than 12 (above that of the single long outfall value).

ACKNOWLEDGMENT

The study was supported by Sultan Qaboos University (IG/SCI/DOMS/10/11), Oman. The author was grateful to the reviewers for their constructive comments in improving the manuscript.

REFERENCES

Al-Barwani, Hamdi H., and Anton Purnama. "Simulating Brine Plumes Discharged into the Seawaters." Desalination 221 (2008): 608-613.

Bleninger, Tobias, and Gerhard H. Jirka. "Modelling and Environmentally Sound Management of Brine Discharges from Desalination Plants." Desalination 221 (2008): 585-597.

Gradshteyn, I. S., and I. Ryzhik. "Tables of Integrals, Series and Products." Academic Press, London, UK, 1980.

Institution of Civil Engineers. "Long Sea Outfalls." Thomas Telford Ltd, London, UK, 2001.

Jirka, Gerhard H. “Integral Model for Turbulent Buoyant Jets in Unbounded Stratified Flows. Part 2: Plane Jet Dynamics Resulting from Multiport Diffuser Jets.” Environmental Fluid Dynamics 6 (2006): 43-100.

Kay, Anthony. “Advection-diffusion in Reversing and Oscillating Flows: 1. The Effect of a Single Reversal.” IMA Journal of Applied Mathematics 45 (1990): 115-137.

Lattemann, Sabine, and Thomas Hopner. “Environmental Impact and Impact Assessment of Seawater Desalination.” Desalination 220 (2008): 1-15.

Macdonald, G. J., and R. N. Weisman. “Oxygen-Sag in a Tidal River.” ASCE Journal of Environmental Engineering 103 (1977): 473-488.

Macqueen, J. F. “Background Water Temperatures and Power Station Discharges.“ Advances in Water Resources 1 (1978): 195-203.

Macqueen, J. F., and R. W. Preston. “Cooling Water Discharges into a Sea with a Sloping Bed.” Water Research 17 (1983): 389-395.

Palomar, Pilar, and Inigo J. Losada. “Impacts of Brine Discharge on the Marine Environment. Modelling as a Predictive Tool.” In Desalination, Trends and Technologies, edited by M. Schorr, 279-310. InTech Open Access Publisher, 2011.

Purnama, Anton. “Merging Effluent Discharge Plumes from Multiport Diffusers on a Sloping Beach.” Applied Mathematics 3 (2012): 80-85.

Purnama, Anton, and Hamdi H. Al-Barwani. “Spreading of Brine Waste Discharges into the Gulf of Oman.” Desalination 195 (2006): 26-31.

Purnama, Anton, Hamdi H. Al-Barwani, Tobias Bleninger, and Robert L. Doneker. “CORMIX Simulations of Brine Discharges from Barka Plants, Oman.” Desalination and Water Treatment 32 (2011): 329-338.

Purnama, Anton, and Anthony Kay. “Effluent Discharges into Tidal Waters: Optimal or Economic Strategy?.” Environmetrics 10 (1999): 601-624.

Roberts, David A., Emma L. Johnston, and Nathan A. Knott. “Impacts of Desalination Plant Discharges on the Marine Environment: A Critical Review of Published Studies.” Water Research 44 (2010): 5117-5128.

Roberts, Philip J. W., and Xiaodong Tian. “New Experimental Techniques for Validation of Marine Discharge Models.” Environmental Modelling and Software 19 (2004): 691-699.

Shao, Dongdong, Adrian W. K. Law, and H. Y. Li. “Brine Discharges into Shallow Coastal Waters with Mean and Oscillatory Tidal Currents.” Journal of Hydro-Environment Research 2 (2008): 91-97.

Sheppard, C., M. Al-Husiani, F. Al-Jamali, F. Al-Yamani, R. Baldwin, J. Bishop, F. Benzoni, E. Dutrieux, N. K. Dulvy, S. R. V. Durvasulla, D. A. Jones, R. Loughland, D. Medio, M. Nithyanandan, G. M. Pilling, I. Polykarpov, A. R. G. Price, S. Purkis, B. Reigl, M. Saburova, K. S. Namin, O. Taylor, S. Wilson, and K. Zainal. “The Gulf: A Young Sea in Decline.” Marine Pollution Bulletin 60 (2010): 13-34.

Signell, Richard P., Harry L. Jenter, and Alan F. Blumberg. “Predicting the Physical Effects of Relocating Boston’s Sewage Outfall.” Journal of Estuarine, Coastal and Shelf Sciences 50 (2000): 59-72.

Smith, Ronald, and Cecil F. Scott. “Mixing in the Tidal Environment.” ASCE Journal of Hydraulic Engineering 123 (1997): 332-340.

Voutchkov, Nikolay. “Overview of Seawater Concentrate Disposal Alternatives.” Desalination 273 (2011): 205-219.